(NASA-CR-159533) EVALUATION OF CERAMICS FOR STATOR APPLICATION: GAS TURBINE ENGINE REPORT Progress Report, 1 Feb. 1978 - 31 Jul. 1978 (Ford Motor Co.) 36 p HC A03/MF A01 CSCL 21E G3/07

N79-21075

Unclas 23946

DOE/NASA/0019-78/1
NASA CR-159533

EVALUATION OF CERAMICS FOR STATOR APPLICATIONS — GAS TURBINE ENGINES

PROGRESS REPORT FOR PERIOD FEB. 1, 1978 TO JUL. 31, 1978

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NOVEMBER 1978

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-00019

for

U.S. DEPARTMENT OF ENERGY

Office of Conservation and Solar Applications
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ABSTRACT

The objective of the DOE/NASA/Ford program entitled "Evaluation of Ceramics for Stator Applications in Gas Turbine Engines" is to assess current ceramic materials, component fabrication processes and reliability prediction capability for ceramic stators in an automotive gas turbine engine environment. Simulated engine duty cycle testing of stators will be conducted at temperatures up to 1093°C (2200°F).

Materials being evaluated are SiC and Si_3N_4 fabricated from two near-net-shape processes: slip casting and injection molding. Participating vendors will be supplying stators for durability cycle evaluation and test specimens for material property characterization. A reliability prediction model will be prepared to predict stator performance in the simulated engine environment.

This report describes the work requirements and proposed technical approaches for the four major technical tasks in the program. Also reported is the status and description of the work performed during the period of February 1, 1978 thru July 31, 1978 for the reliability prediction modeling, stator fabrication, material property characterization, and ceramic stator evaluation efforts.

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SUMMARY

Results obtained for the work period of February 1, 1978 through July 31, 1978 are presented for each of the four technical tasks within the project.

TASK I — RELIABILITY PREDICTION MODEL

A 3-D finite element model of the stator has been completed. Heat transfer coefficients were prepared and thermal analyses completed for the first 15 seconds following a simulated light-off transient. Constant material properties were assumed. Programming has begun for inclusion of aerodynamic loads for future stress analysis.

TASK II — STATOR FABRICATION

Negotiations were successfully completed for participation of three ceramic component suppliers in addition to two separate Ford material programs. Outside suppliers are AiResearch, Carborundum and Norton. The five approaches represent two basic near-net-shape processes — slip casting and injection molding — in both the SiC and Si_3N_4 materials. Tooling and/or stator fabrication is underway for all five approaches.

TASK III — MATERIAL PROPERTY CHARACTERIZATION

The Illinois Institute of Technology Research Institute (IITRI) has been subcontracted for characterizing the five suppliers' materials for Young's and shear modulii, as well as thermal diffusivity, specific heat and thermal conductivity.

Fixtures for hot modulus of rupture (MOR) strength characterization at Ford have been designed and ordered. Dilatometer modifications have been completed at Ford for thermal expansion characterization.

TASK IV — CERAMIC STATOR EVALUATION

Automation of the duty cycle test rig is in process. An automatic control specification was prepared and a control system ordered. Rig testing was conducted to define system characteristics and obtain control design data. Combustor development was conducted to improve lean blow-out margin at minimum duty cycle temperature conditions.

INTRODUCTION

Ford Motor Company started research on applying brittle materials to gas turbine engines in 1961 when development was initiated on a ceramic regenerator system for use in gas turbine engines. In 1967, work on high temperature turbine research was started along with initial design investigations of an experimental high temperature gas turbine engine, designated Model 820.

By the end of 1970, based on design studies and experimental research, it was decided to concentrate research and development on an all-ceramic flowpath rather than on using an air-cooled metal turbine wheel. Since 1971 government funding has helped to accelerate the development of such ceramic turbine technology. Progress on these programs has been of considerable interest to the technical community and has spurred the establishment of activities in ceramic material and process development and ceramic turbine component and engine development on a worldwide basis.

Of particular interest are the areas of ceramic structural component technology, comprising:

- Designing with ceramics
- Ceramic material and process development
- Ceramic test rig development
- Ceramic component testing methodology
- Reliability prediction and failure analysis

As a step in the progression of events, the Department of Energy (through NASA-Lewis) initiated a program in January, 1978 which would provide for an assessment of the capability of the ceramics industry to fabricate ceramic gas turbine engine one-piece stators having the quality and integrity required for automotive turbine engine applications.

Ceramic stators of the Ford Model 820 turbine engine design were selected for this program. This stator is representative of size and design required for automotive turbine engines, prior experience exists in fabricating silicon nitride and silicon carbide stators of this design, and rig and engine tests have been conducted with these components.

The work to be accomplished under the program, "Evaluation of Ceramics for Stator Applications — Gas Turbine Engines," is divided into four technical tasks that include development of a reliability prediction model for ceramic stators, fabrication of ceramic stators, material property characterization, and simulated engine duty cycle testing of the stators.

Ceramic stators will be fabricated by Ford and three ceramic component suppliers using fabrication techniques that have potential for near-net-shape, mass production. Baseline ceramic material properties will be determined, as required, for input to the reliability prediction model.

DISCUSSION OF PROGRAM

TASK I — RELIABILITY PREDICTION MODEL

I. A. Scope of Work

In this task a reliability prediction model will be prepared for the current ceramic stator design of the Ford Model 820 automotive gas turbine engine. The general requirements for the model to be developed are outlined below.

1. The reliability prediction model must be designed to predict stator performance associated with driving a vehicle powered by a gas turbine engine over a driving cycle as simulated in the Ford Hot Flowpath Qualification Rig and Light Off Qualification Rig.

2. Development of the model must incorporate a detailed analysis which includes a 3-D finite element analysis of the stator to provide the stress distribution. This analysis must account for stresses imposed on the stator by both aerodynamic loading and thermal transients associated with the simulated engine test.

3. Variability normally encountered in ceramic materials must be accounted for by using statistical material strength parameters.

4. The model must account for ceramic component failure due to time independent and time dependent failure modes. For time dependent failure, at least slow crack growth must be included for those materials exhibiting this phenomena.

5. Model construction must be such that for any given ceramic material, the reliability of a stator fabricated from that material can be predicted from known base material properties.

I. B. Technical Approach

In developing the reliability prediction model for the ceramic stator a sequence of analytical steps utilizing an assortment of computer programs is planned. A flow chart of the sequence is shown in Figure 1.

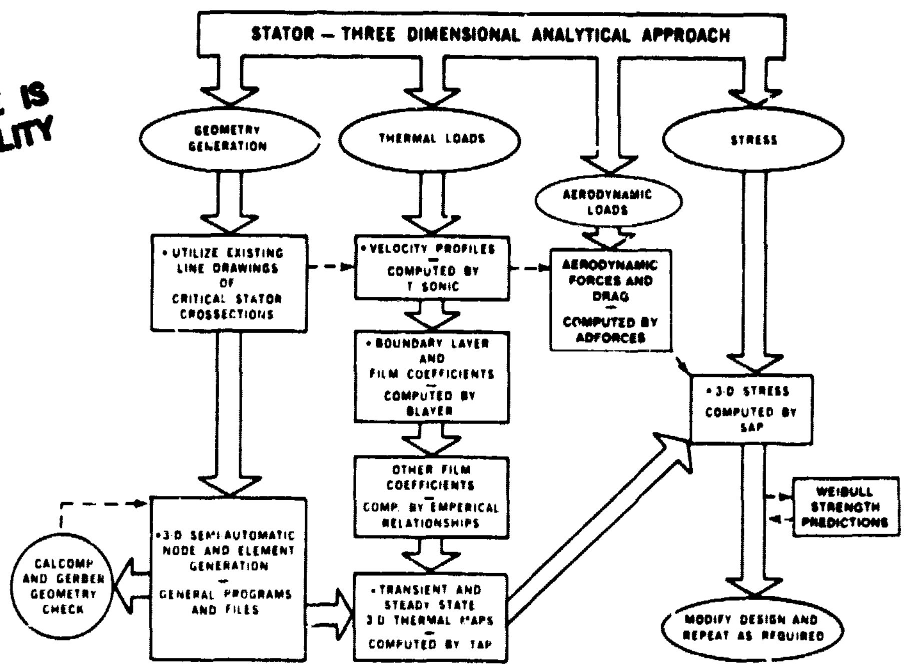


Figure 1 Schematic of Typical Three-Dimensional Analysis Process

Development of the 3-D finite element model will include a 1/25 section of the stator. The section will include the outer shroud, a complete vane and the attached inner shroud segment. Element layout at the ends of the outer shroud sections will be such as to permit forcing displacement continuity with the adjacent, but not included, elements.

Thermal boundary conditions for the model will be sufficiently established to carry out a 3-dimensional heat transfer analysis. Convective film coefficients for the vane surfaces will be obtained directly from the Nusselt number output computed by BLAYER which was developed by NASA for computing 2-dimensional boundary layers on airfoils and turbomachine blades in arbitrary pressure gradients (1). The velocity distribution, an input requirement of BLAYER, is computed by TSONIC, also developed by NASA (2). Film coefficients for the wetted surfaces of the inner and outer shrouds are computed by an empirical method given by Zysina-Molozhen and Uskov (3).

Temperature distributions throughout the model will be generated using a modified version of the commercially available TAP program developed by Engineering/Analysis Corporation (4). This program allows for heat transfer analysis by convection and conduction to a constant environment through a fixed surface heat transfer coefficient. Thermal properties (conductivity and specific heat) will be temperature dependent where applicable.

External loads imposed on the model consist essentially of aerodynamic forces on the vane and will be included in the stress analysis. Calculation of these forces will be obtained from the pressures or velocities along the surfaces using the NASA developed ADFORCES program (5).

Stress distributions throughout the model will be obtained from the combination of external aerodynamic forces and thermal gradients. A modified version of the commercially available SAP IV program developed by the Department of Structural Engineering, University of California (6) will be used. The program allows for the study of multiple thermal loads and can handle elastic and thermal expansion properties which are fully orthotropic and vary with temperature. Sufficient stress mapping will be performed to provide a visual display of the stress contours at critical loading conditions.

Reliability prediction for the time independent analysis will use the output from the stress analysis to determine the probability of survival of the stator for the loading conditions imposed by the durability test. The material properties required for the analysis are the characteristic strength and Weibull modulus measured as a function of temperature.

The time dependent life-prediction portion of the system uses output from the strength analysis to determine the useful life of the stator under a constant or varying load history. The analysis is based on the model for subcritical crack growth (7) and used fatigue strength parameters as input. The static fatigue strength parameters consist of the characteristic strength of an MOR test bar and the corresponding stress rate ($\dot{\sigma}$) at which these measurements are taken. The crack propagation exponent is obtained directly from static fatigue strength measurements conducted at different stress rates.

I. C. Status

The initial efforts on the reliability prediction model were directed toward establishing base line data on the Ford computer system, repeating an earlier stator analysis. The previous analysis was prepared by the Lawrence Livermore Laboratory (LLL) for the U. S. Energy Research and Development Administration under contract number W-7405-ENG-48 (8). The LLL study included a finite element 3-D model and utilized finite element thermal and stress analysis. However, the analysis had a number of shortcomings relative to the scope of this current program. It was based on an earlier design Ford stator, did not include temperature dependent properties or aerodynamic loads, employed simplified boundary constraints and did not include reliability prediction.

Reinstatement of available computer files representative of the LLL analysis was completed. Thermal gradients and thermal stress data was generated using the reinstated tapes and files.

A completely revised 3-D finite element model has been developed and appears as an exploded view in Figure 2. The new model includes a one blade section (1/25) of the outer shroud, one complete vane and its attached inner shroud segment. Outer shroud element layout has been prepared in such a way as to enable forcing deflection continuity at both ends for the stress analysis.

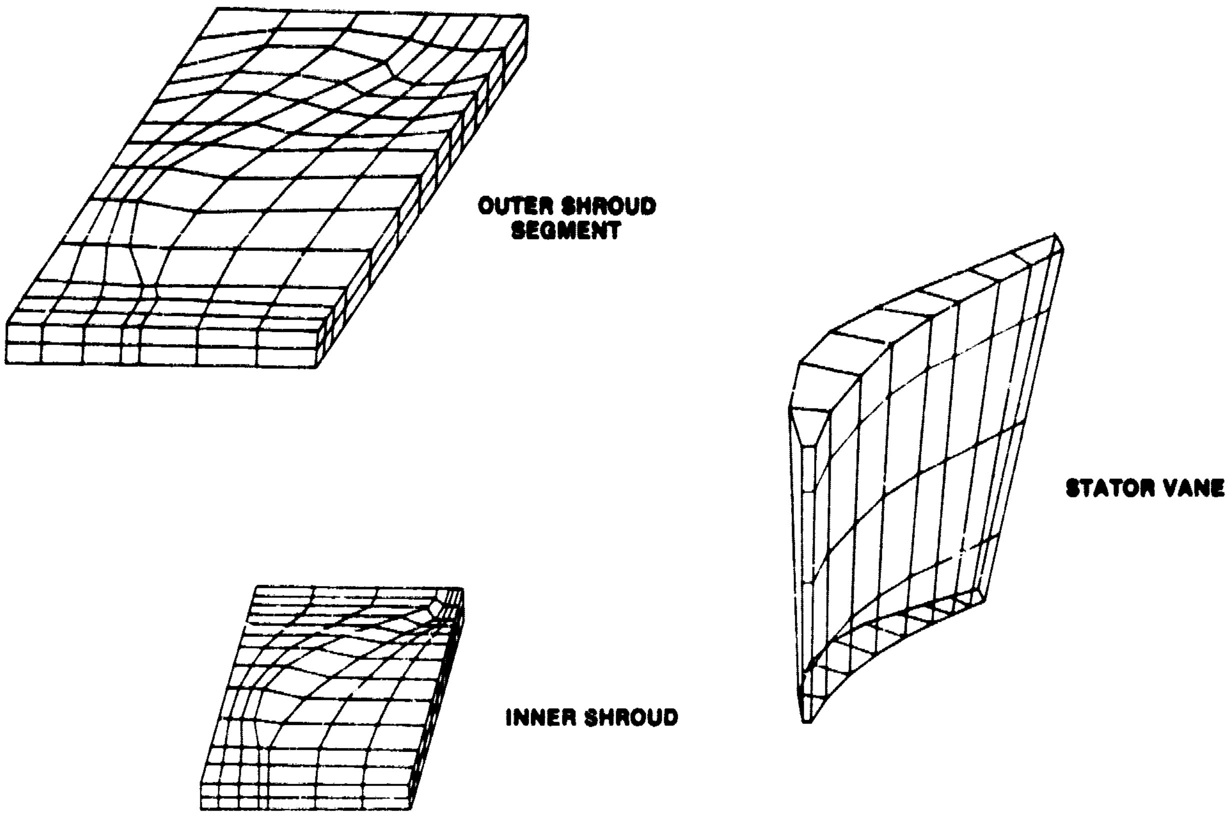
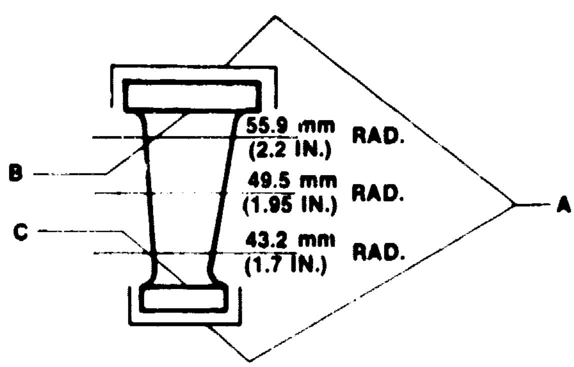


Figure 2 Three-Dimensional Model of Ford Model 820 Ceramic Stator

Heat transfer coefficients representative of a cold light off-to-engine idle transient have been prepared for the new model thermal analysis. Coefficients for the wetted surfaces of the inner and outer shrouds are shown in Figure 3. Blade surface film coefficients for the pressure and suction surfaces of the four layers of elements are shown in Figures 4, 5 & 6 as a function of the dimensionless surface distance S/Smax. The three dimensional coefficients shown on these figures were obtained by interpolation and extrapolation of two dimensional data generated for blade profiles at 43.2, 49.5 & 55.9mm (1.70, 1.95 & 2.2 inch) radii from the stator center line (9).



SURFACE(S)	HEAT TRANSFER COEFFICIENT W/m²K (BTU/hr ft² R)
A	0 (INSULATED)
B	850 (150)
C	891 (157)

Figure 3 Heat Transfer Film Coefficients for Thermal Analysis

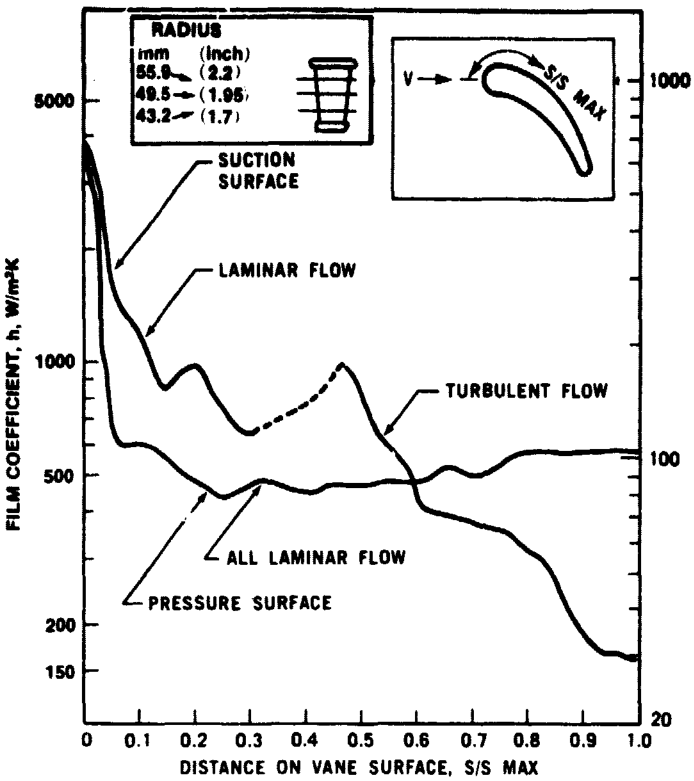


Figure 4 Heat Transfer Film Coefficients, First Stage Stator Vane at 55% Speed, 1054°C (1930°F) Inlet Temperature and Radius of 43.2mm (1.7 in.)

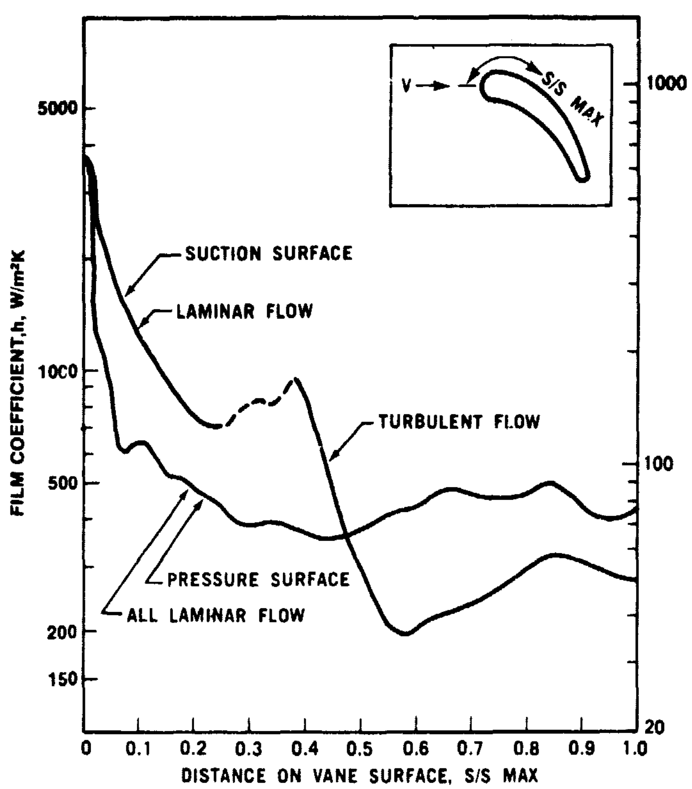


Figure 5 Heat Transfer Film Coefficients, First Stage Stator Vane at 55% Speed, 1054°C (1930°F) Inlet Temperature and Radius of 49.5mm (1.95 in.)

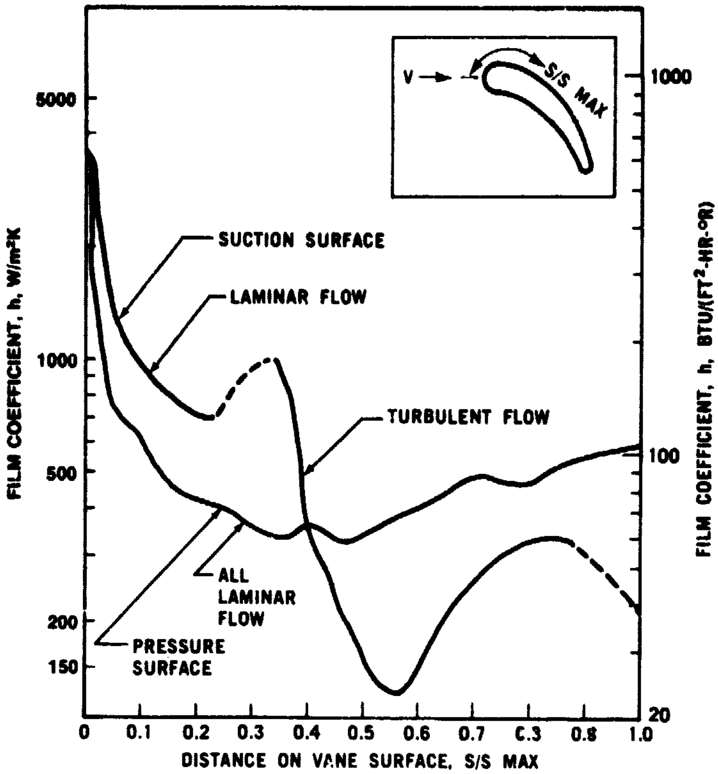


Figure 6 **Heat Transfer Film Coefficients, First Stage Stator Vane at 55% Speed, 1054°C (1930°F) Inlet Temperature and Radius of 55.9mm (2.2 in.)**

Thermal gradients have been computed for the first 15 seconds of a simulated qualification test light off with the new model and using the heat transfer coefficients shown. Material properties used were those at 538°C (1000°F) for the Ford 2.7 g/cc density, injection molded, reaction bonded Si_3N_4. The specific property values are shown in Table 1.

YOUNG'S MODULUS, MPa (PSI)	166×10^3	(24.1×10^6)
SHEAR MODULUS, MPa (PSI)	71×10^3	(10.3×10^6)
THERMAL EXPANSION, cm/cm°C (in/in°F)	2.59×10^{-6}	(1.46×10^{-6})
POISSON RATIO	.164	(.164)
THERMAL CONDUCTIVITY, W/mK (BTU/hr ft°F)	1.17	(.675)
SPECIFIC HEAT, J/kgK (BTU/Lb °F)	1130	(.270)

Table 1. Properties of Ford Injection Molded Reaction Bonded Silicon Nitride at 538°C (1000°F).

Temperature contours for the stator vane pressure and suction surfaces at 2.0 and 5.0 seconds are shown in Figures 7 and 8. Thermal stresses have also been generated using the new model.

Work is in process for the addition of the aerodynamic loads to the stress analysis. The NASA program for calculating these aerodynamic loads (ADFORCES) is being compiled in the FORTRAN IV system and also in modified form for use with the Honeywell FORTRAN system.

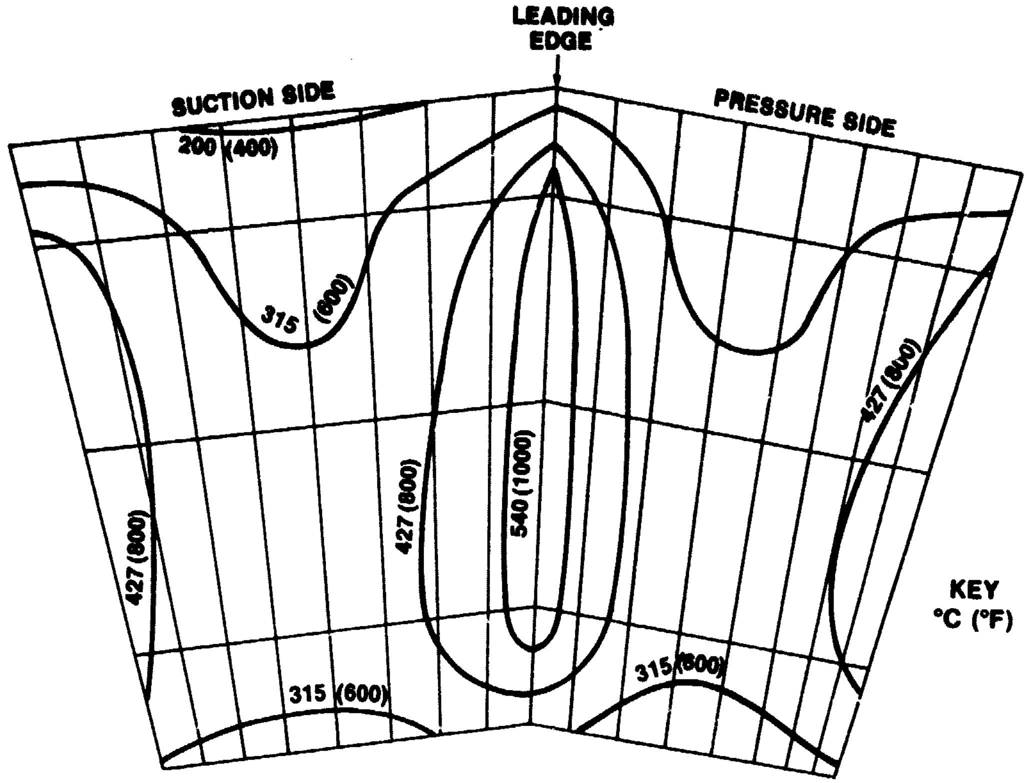


Figure 7 Temperature Profile on Stator Vane Surfaces 2.0 Seconds after a Step Change in Gas Temperature from 16 to 1054°C (60 to 1930°F).

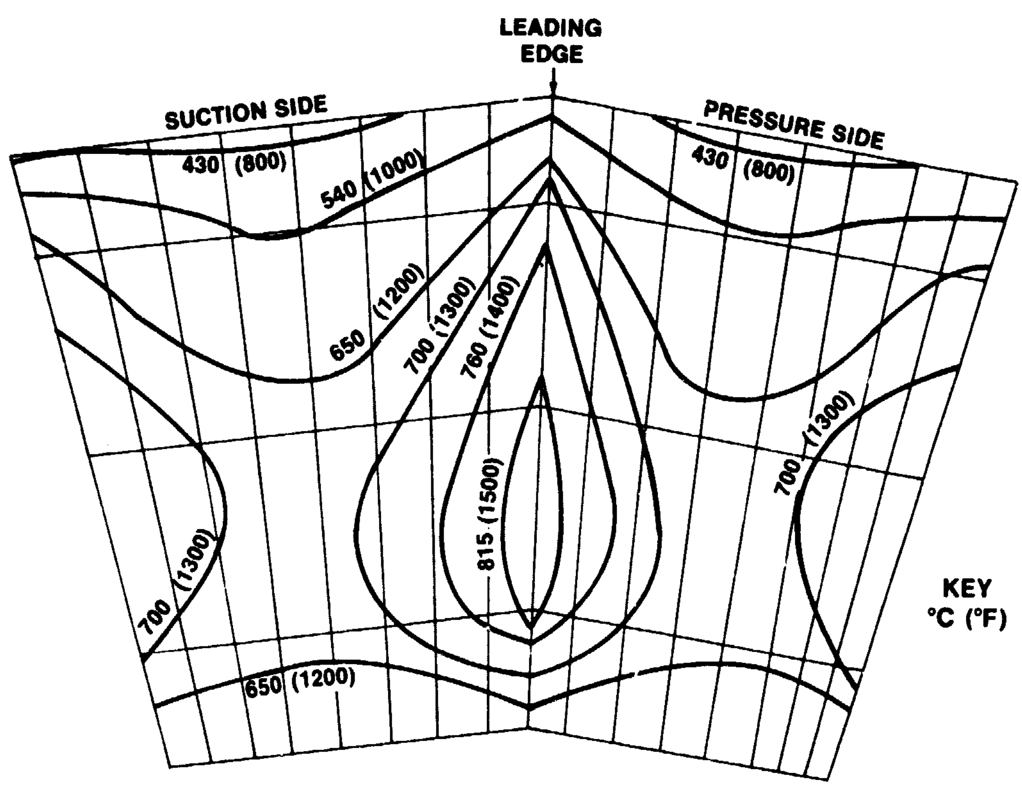


Figure 8 Temperature Profile on Stator Vane Surfaces 5.0 Seconds after a Step Change in Gas Temperature from 16 to 1054°C (60 to 1930°F).

I. D. Problem Areas

No problems at this point in the program.

I. E. Work Planned

Addition of the aerodynamic forces in the stress analysis will be completed and an assessment made of the influence of these forces on stress magnitude and distribution. Stress program input for use of temperature dependent material properties will be prepared and checked out. Reliability prediction for time independent failure mode will be performed for those stators for which material properties are obtained in the Task III — Material Property Characterization-effort.

TASK II — STATOR FABRICATION

II. A. Scope of Work

Silicon nitride and silicon carbide one-piece ceramic stators of the current Ford Model 820 design are to be fabricated under this task for subsequent evaluation in the Task IV — Stator Evaluation-effort. General requirements for the stators, fabrication processes and vendors are outlined below.

1. Ceramic stators are to be fabricated from both Si_3N_4 and SiC materials and include at least three ceramic component suppliers. Fabrication of stators from both materials by any ceramic component supplier is not required.

2. Stator fabrication processes selected for this program must have potential for near-net-shape, low cost production.

3. Stators obtained from ceramic suppliers and of each ceramic material are to meet the test requirements of Task IV. As a minimum, each ceramic supplier must provide 12 stators of a material and process selected for evaluation.

In addition to the twelve stators, each ceramic supplier must submit a sufficient quantity of physical property test specimens and MOR bars for use in the Task III — Material Property Characterization-effort. Test specimens and bars supplied must be representative of the starting material and process conditions used to fabricate the stators.

Other ceramic hardware required to support test rigs for Task IV, — such as turbine inlet nose cones, inner liners and tip shrouds are to be furnished by Ford and are to be of materials and design which provide adequate reliability for conducting the stator tests.

II. B. Technical Approach

Two fabrication efforts will be conducted at Ford. Each will supply a complete set of stators, MOR bars and physical property specimens for evaluation in this program. One program will use Si C material; the other will use Si_3N_4.

Tooling and technology employed in the Ford efforts will take advantage of the stator fabrication experience gained from earlier Ford and government programs related to injection molding research and development.

Automatic control of the injection molding process and parameters will be employed to improve quality control and repeatability in the fabrication of stators. MOR test bar cavities are included in the stator die to insure fabrication of test bars representative of the stator material and process.

New physical property specimen tooling will be designed and fabricated. Actual molding of specimens will be performed using the same molding machine and controls as used for stators. Special tooling adaptors for both the stator die and physical property die will be designed and fabricated for use with the SiC material. The need for such adaptors results from the use of a thermosetting polymer with the SiC starting materials.

Participation by ceramic component suppliers will be achieved through subcontracts negotiated by Ford and concurred by NASA. Each subcontract will specify fabrication of stators, MOR bars and physical property specimens in general conformance with the requirements outlined in the Scope of Work. Both SiC and Si_3N_4 material will be represented in the subcontracts. Near-net-shape processes of injection molding and slip casting will be represented.

Ceramic support hardware such as turbine inlet nose cones, inner liners and tip shrouds for the Task IV test rigs will use similar materials, processes and designs as have been employed in earlier Ford/government ceramic turbine technology programs. A complete set of typical ceramic components for the Hot Flowpath Qualification Rig are shown in Figures 9 and 10. A schematic of the Engine Simulator Rig is shown in Figure 11.

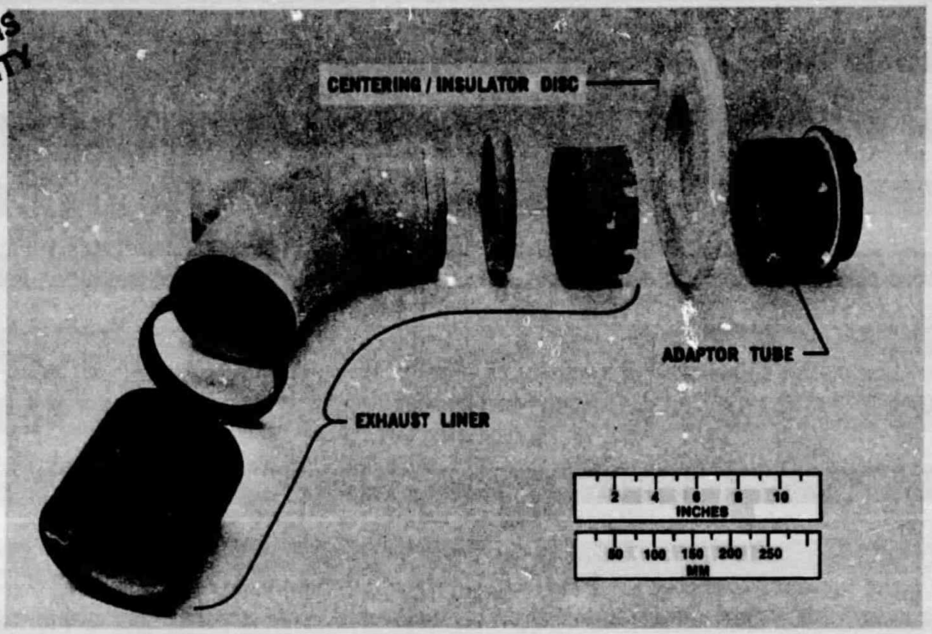


Figure 9 Structural Ceramic Components Used in Durability Cycle Test Rig

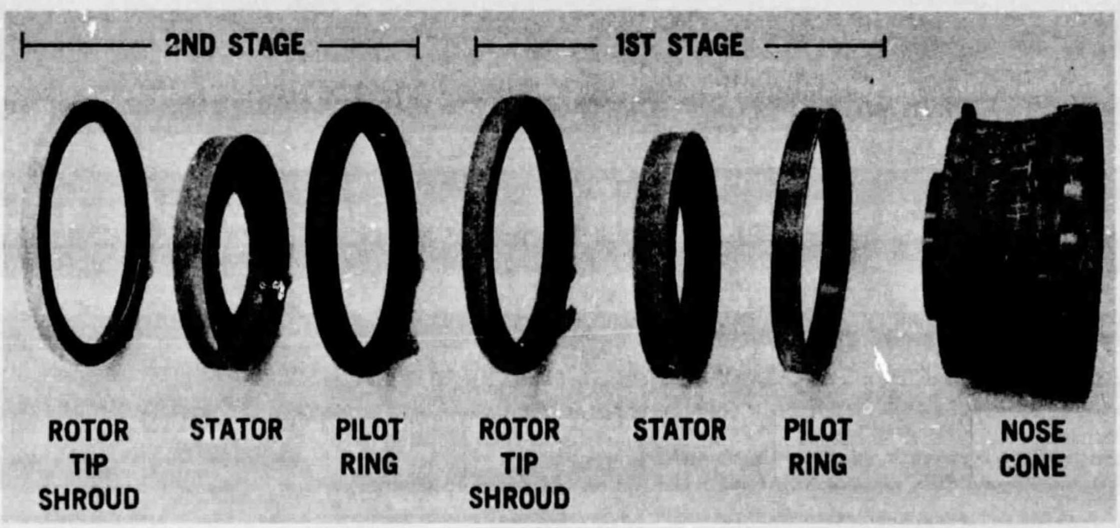


Figure 10 Ceramic Hot Flowpath Components Used in Durability Cycle Test Rig

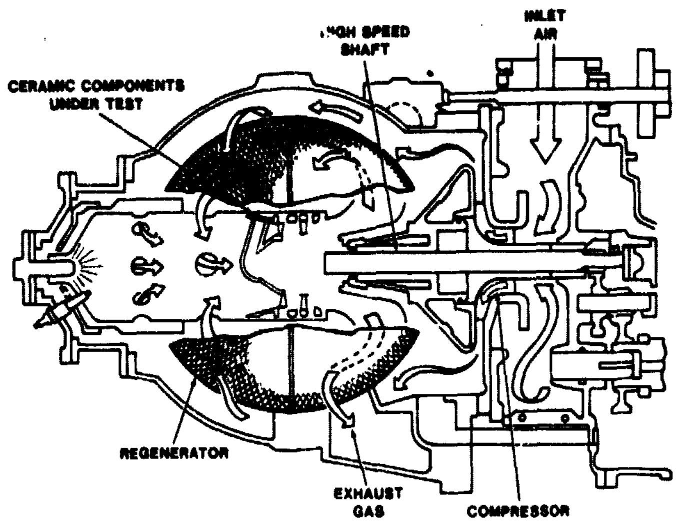


Figure 11 Schematic Cross-Section of Engine Simulator Rig

II. C. Status

In addition to the two Ford stator fabrication programs, subcontracts have been placed with three outside ceramic component suppliers. They are AiResearch Casting Co., Carborundum Co. and Norton Co. The five vendors now provide for an evaluation of two basic near-net-shape processes in both the Si_3N_4 and SiC materials. The specific vendors, processes and materials are summarized in Table 2.

Vendor	Fabrication Process	Material
Ford	Injection Molded, Reaction Bonded	Si_3N_4
Ford	Injection Molded, Silicided	SiC
Airesearch	Slip Cast, Reaction Bonded	Si_3N_4 (Airceram RBN-101)
Carborundum	Injection Molded, Sintered	SiC (α Phase)
Norton	Slip Cast, Sintered	SiC (Noralide NC-433)

Table 2. Fabrication Processes, Materials and Participants in the Stator Evaluation Program.

The specific hardware to be furnished by each of the suppliers is detailed in Table 3. RTR numbers appearing in the table are Ford Motor Company drawing numbers.

	12 STATORS	
RTR-0968	Casting	AiResearch, Carborundum[1]
RTR-1206	Finish Machined	Ford, Ford, Norton
	300 MOR BARS	
RTR-1970	Machined 3 Sides	Norton
RTR-1971	Slip Cast	AiResearch
RTR-1972	Injection Molded	Ford, Ford, Carborundum
	PHYSICAL PROPERTY SPECIMENS[2]	
RTR-1986	Billet[3]	Carborundum
RTR-1973 (5)	Thermal Diffusivity	Ford, Ford, AiResearch, Norton
RTR-1974 (10)	Specific Heat	Ford, Ford, AiResearch, Norton
RTR-1987 (10)	Sonic Modulus	Ford, Ford, AiResearch, Norton

1 To be finish machined @ Ford before durability test.
2 RTR-1974 Re-machined for thermal expansion specimen after specific heat evaluation.
3 To be finish machined @ Ford into RTR. — 1973, 1974 & 1987 specimens.

Table 3. Ceramic Components Required for Task III Material Property Characterization and Task IV Ceramic Stator Evaluation.

The AiResearch subcontract purchase order was placed in June. Prior to placement of the purchase order, arrangements were made with AiResearch to fabricate wax patterns with the Ford stator tool using pattern material supplied directly by AiResearch. A total of 56 wax patterns were produced and have been delivered to AiResearch where ceramic stator fabrication is now underway. The hardware delivery schedule calls for delivery to Ford of two stators in September with the balance of the order to be completed in December, 1978.

The Carborundum subcontract purchase order was also placed in June. Work now underway at Carborundum involves the design and fabrication of the stator and physical property dies. Program timing calls for delivery of the physical property billets between October, 1978 and February, 1979. Stator and MOR bar deliveries begin in February and are to be completed in May, 1979.

The Norton subcontract purchase order was placed in April and authorized Norton to proceed with Phase I (Pilot Run) of their two phase program. Wax patterns, required in the Norton process, were fabricated from two different material compositions supplied by Norton. Thirty-five patterns were produced from each material and delivered to Norton.

The Phase I effort is now underway and is intended to optimize the casting procedure for the stator shape defined by Ford drawing RTR-1206. Tooling for the expendable casting process and for finish machining will also be completed. Hardware to be fabricated and delivered during this phase includes : 2 stators, 50 MOR test bars, and all 25 physical property samples. Of the two stators, one will be finish machined and shipped to Ford for inspection while the other will be retained at Norton for material characterization. Phase I completion is projected for September. Phase II (Production Run) will complete the fabrication and delivery of 12 additional stators and the balance (250) of the MOR bars. Phase II completion is projected for December, 1978.

Injection molding of Si_3N_4 and SiC stators and test specimens at Ford is being carried out in series since common tooling, molding machine and controls are used. The molding of the Si_3N_4 components is proceeding first while special tooling is being designed for adapting the dies for SiC molding.

A new vertical clamping injection molder is being used on the Ford programs. As such it was necessary to install and check out the associated hydraulic and electronic equipment used for process and parameter control. Photographs of the molder and control equipment are shown in Figures 12 and 13. Installation and check out have now been completed. However, during molder clamping tryouts with the stator die, unacceptable molder platten deflections were observed. The excessive platten deflections were overcome by selectively shimming the stator die between the die base and lower platten.

Stator molding has been started and to date 24 stators, plus the 48 associated MOR bars, have been fabricated. These stators and bars have been processed through visual and x-ray inspection. Half of these components have also been processed through binder burn-out and revealed no burn-out related problems.

The billet die for the physical property specimens was designed, fabricated, installed and checked out. A total of 42 Si_3N_4 billets were molded, including those during die try-out. X-radiography inspection revealed voids in several parts and the presence of flow lines in a number of others. A sufficient quantity of acceptable billets are available for machining the physical property specimens required for Task III and will be continued through nitridation.

The SiC molding effort at Ford has concentrated on tooling preparation. Pot and plunger adaptor hardware has been designed for both the stator and billet dies. Fabrication of the adaptors for the stator tool has been completed. The billet die adaptors are in process. The SiC starting material preparation has begun.

Processing of new ceramic support hardware for the Hot Flowpath Qualification Rig and the Engine Simulator Rig is proceeding. To date, seventy-one components have been started, of which twenty-three have been completed. In addition, four existing ceramic liners for the exhaust section of the Hot Flowpath Qualification Rig are being remachined to current print dimensions.

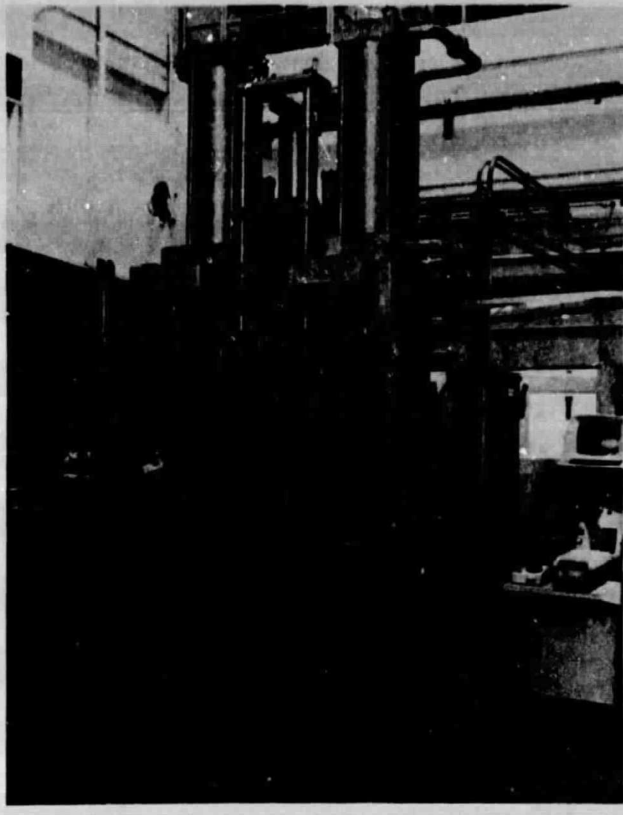


Figure 12 Vertical Clamping Injection Molder Being Used for Ford Stator Fabrication

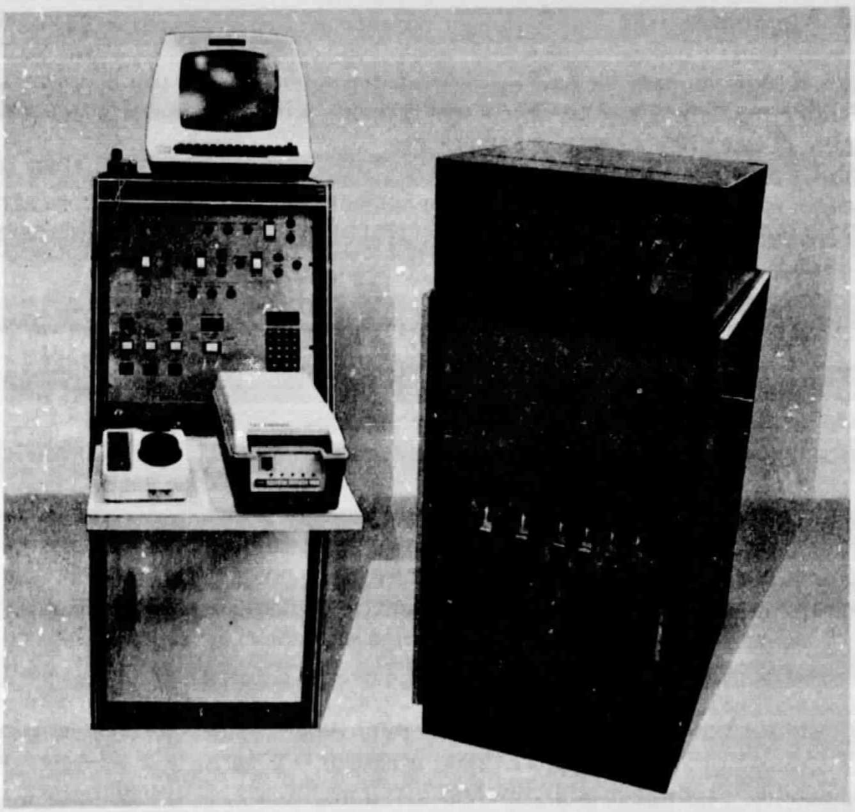


Figure 13 Process Control Equipment for Vertical Clamping Injection Molder

II. D. Problem Areas

Delays encountered in negotiating the supplier subcontracts and molder deflection problems at Ford have resulted in approximately a one month extension in the completion dates for this task.

II. E. Work Planned

During the next six months close coordination will be maintained with the subcontracted ceramic suppliers to insure delivery of the hardware as is now projected. The delivery should include a complete set of hardware from AiResearch and Norton. Physical property billets from Carborundum will be machined into the specific test specimens for the Task III characterization.

Ford Si_3N_4 component fabrication will be completed. Ford SiC tooling will be completed. Injection molding of stators and billets will be completed.

TASK III — MATERIAL PROPERTY CHARACTERIZATION

III. A. Scope of Work

In this task the mechanical and physical property characteristics of each ceramic stator material used for fabrication of stators in Task II are to be determined. All test data is to be obtained from material samples that are representative of the starting materials and process conditions used to fabricate the stators.

The mechanical and physical properties to be obtained are those necessary to satisfy the reliability prediction model requirements of Task I. Materials properties include Young's modulus, shear modulus, thermal conductivity, thermal diffusivity, specific heat, and thermal expansion-all as a function of temperature from ambient to 1204°C (2200°F). Mechanical properties include four-point MOR strength determined statistically as a function of temperature from ambient to 1204°C (2200°F).

III. B. Technical Approach

In order to provide a common base for the five participating vendors in the characterization of their material and the Task I reliability prediction, any given material property will be evaluated by a single source. This will help insure uniformity of test procedures and equipment.

On the above basis, it is planned to have IITRI evaluate the physical properties of thermal diffusivity, specific heat, thermal conductivity, Young's modulus and shear modulus. Evaluation of thermal expansion and statistical modulus of rupture (MOR) will be performed at Ford.

Engineering drawing references for the test specimens have been previously identified in Table 3, Task II. Specific procedures and equipment to be used are described in the following paragraphs.

Thermal diffusivity will be measured by the laser pulse technique. The equipment used is shown in Figures 14 & 15. The sample is contained in a suitable furnace with a zirconia sample holder. The front face of the sample is irradiated with a pulse of energy from a pulsed ruby laser (25 joules, 500 μ sec). The thermal diffusivity is computed from the resulting sample rear face transient temperature response. At room temperature the sample temperature time response is measured with a liquid nitrogen-cooled indium antimonide infrared detector, but with the energy focused on the detector by use of an ir-transmitting lens system. From 816°C to 1370°C (1500°F to 2500°F) another furnace is used, along with a biased silicon photodiode detector to detect the temperature transient. Data will be acquired over the temperature range of ambient to 1204°C (2200°F).

The specific heat will be measured from 93°C to 1204°C (200°F to 2200°F) using a drop calorimetric technique wherein the sample is heated to a uniform elevated temperature and dropped into an adiabatic water calorimeter maintained at room temperature. The equipment used is shown in Figures 16 & 17. Above 980°C (1800°F) the sample may be contained in a capsule to minimize heat loss from the sample during the drop from the furnace to the calorimeter. The heat content (change in enthalpy) of the sample is determined from the temperature rise of

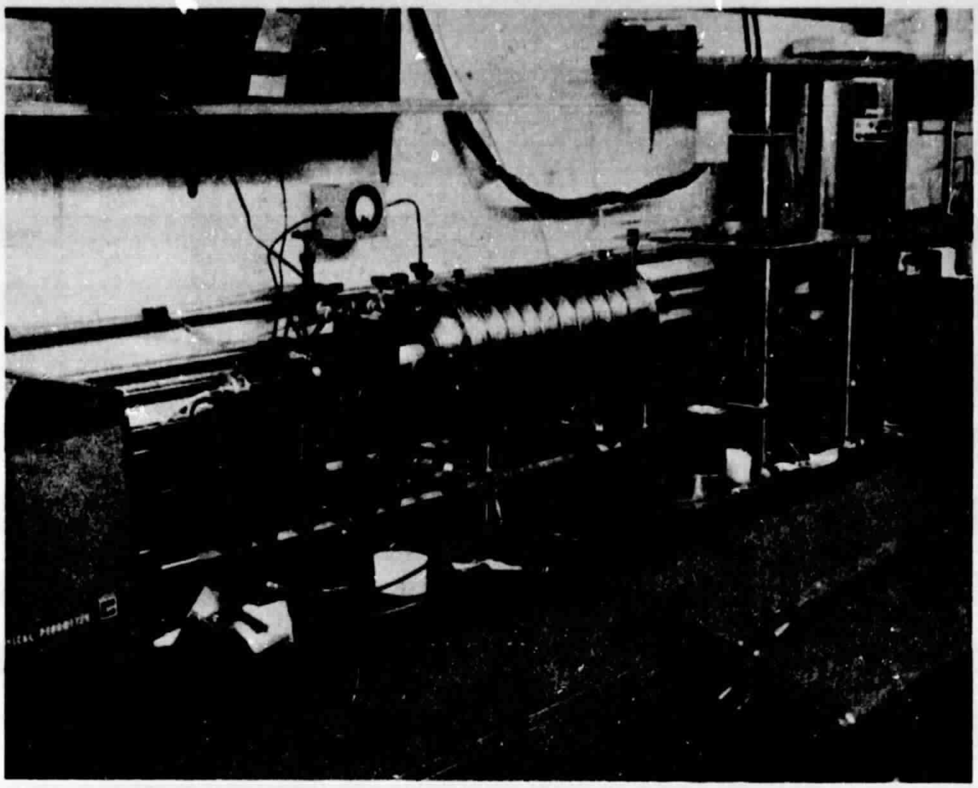


Figure 14 Thermal Diffusivity Test Apparatus at IITRI

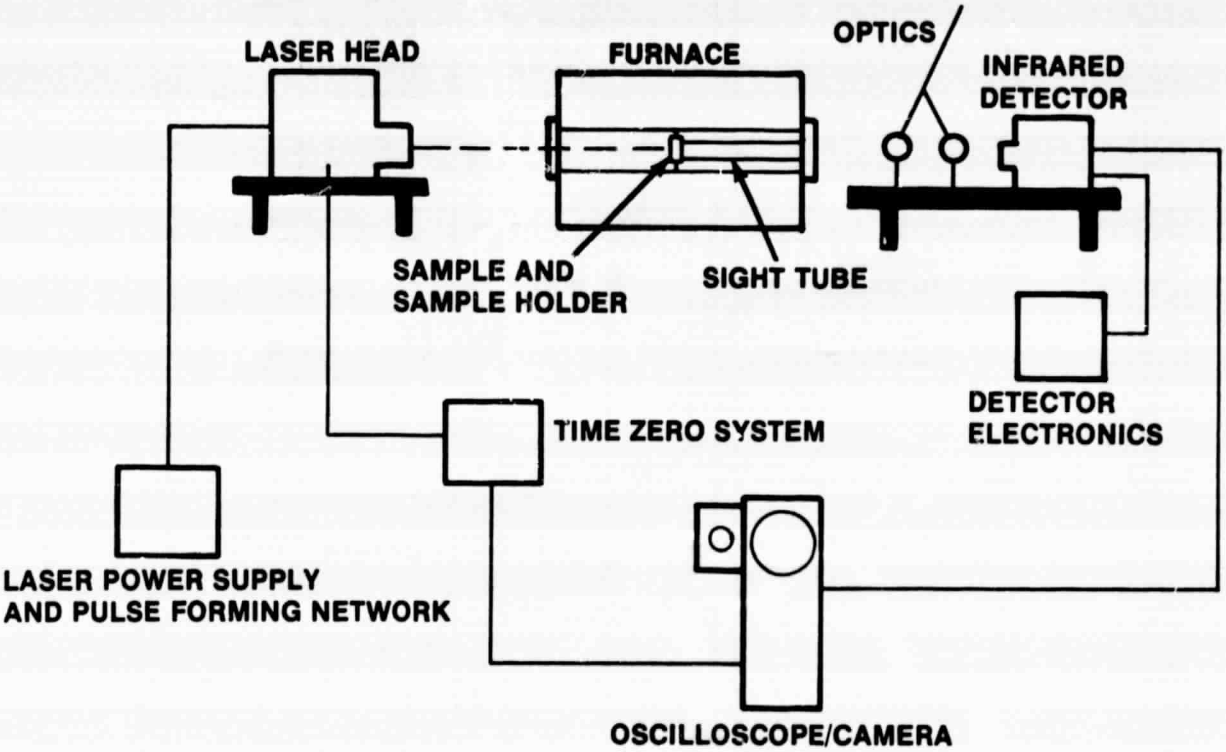


Figure 15 Schematic of Laser Flash Diffusivity Apparatus at IITRI

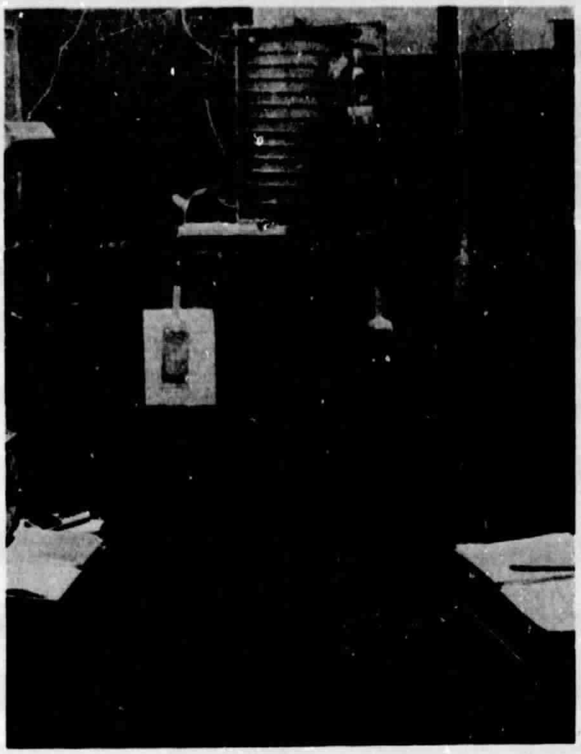


Figure 16 Specific Heat Evaluation Test Apparatus at IITRI

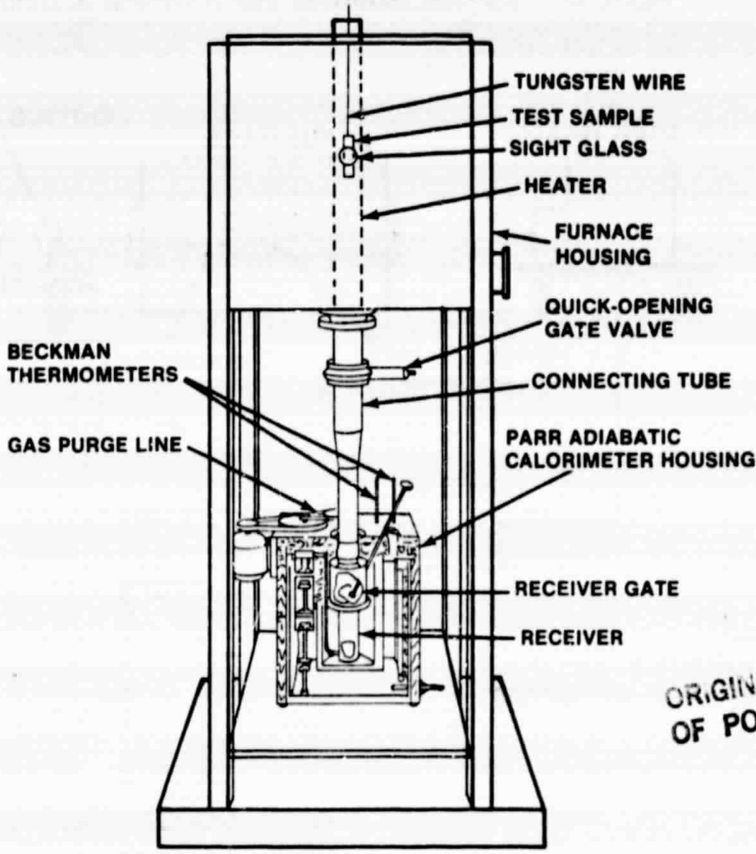


Figure 17 Schematic Diagram of Apparatus for Measuring Specific Heat at IITRI

the calorimeter fluid as the sample cools from the initial state. Corrections are applied for the heat content of the capsule when used. Several drops are required at various initial temperatures to establish an enthalpy-temperature curve for the sample. Curve fitting techniques are employed to express data algebraically. Differentiation of the enthalpy-temperature data gives the specific heat which is evaluated at the desired temperatures. Data will be acquired over the temperature range of ambient to 1204°C (2200°F).

Thermal conductivity is derived as the product of thermal diffusivity, specific heat and density. Data will be calculated over the temperature range of ambient to 1204°C (2200°F).

Both Young's and Shear moduli (and, hence, Poisson's Ratio) will be obtained by IITRI from the resonant frequency of flexural and torsional vibrational modes. A schematic of the system used is shown in Figure 18. In testing, the sample is supended from two piezo-electric transducers, seen in Figure 19 in the flexural mode. Cotton thread is used at room temperature, while SiO_2 yarn, platinum or tungsten wire are used at elevated temperature. An amplified oscillator signal is used to energize the first transducer, which in turn vibrates the sample. The vibration is picked up by the second transducer after traveling through the sample and is measured using a frequency counter. By observing a meter and/or scope while varying the oscillator frequency, the maximum (resonant) frequency can be found. Using this method, elastic moduli can be determined up to 1500°C (2730°F) in air and 1200°C (2190°F) in vacuum or other atmospheres. Data will be acquired over the continuous temperature range of ambient to 1204°C (2200°F).

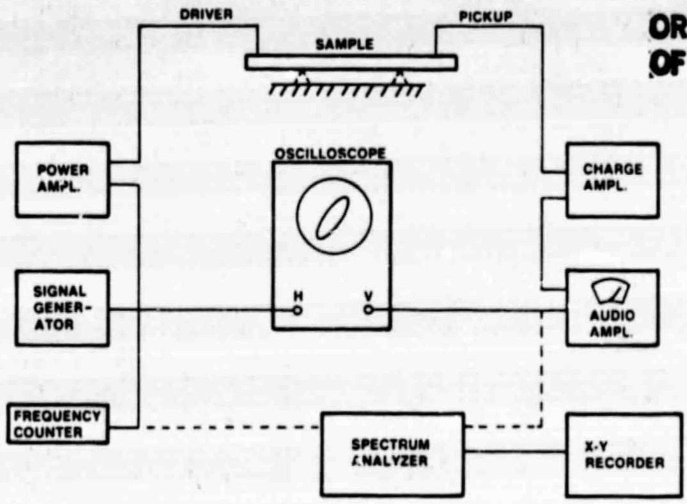


Figure 18 **Schematic of Dynamic Modulus and Internal Friction Apparatus at IITRI**

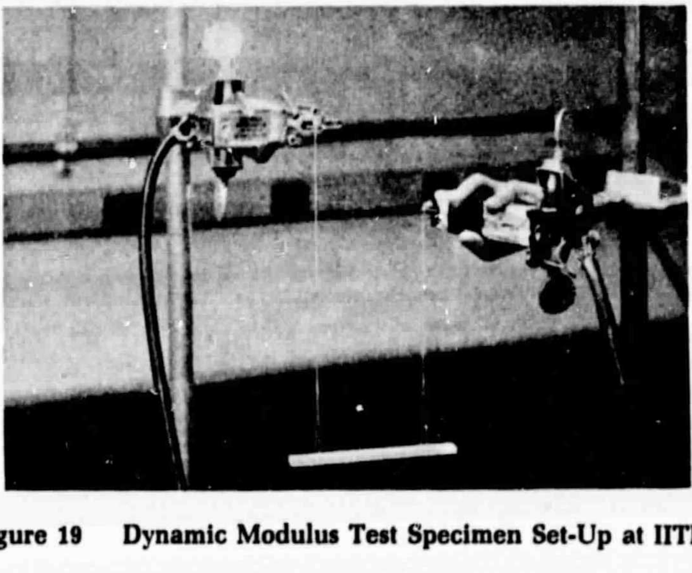


Figure 19 **Dynamic Modulus Test Specimen Set-Up at IITRI**

Thermal expansion will be measured using a differential expansion technique in which the dimensional changes are compared to those of a known single crystal supplier reference sample. The equipment used is shown in Figure 20. Two-inch specimens are tested, with flat and parallel ends, ground to a length of 50.800 ± .013mm (2.000 ± 0.0005 inches). They are supported in a sintered alumina tube, and the length changes detected with alumina push rods. The rod bearing against the reference sample is mounted on the coil, and the rod bearing on the test specimen is attached to the movable core of a Theta linear differential transformer. The core motion relative to the coil is directly proportional to the difference in expansion of the test sample and the reference sample, and the electrical signal produced is amplified and recorded to provide the expansion data. Data will be acquired over the temperature range of ambient to 1204°C (2200°F).

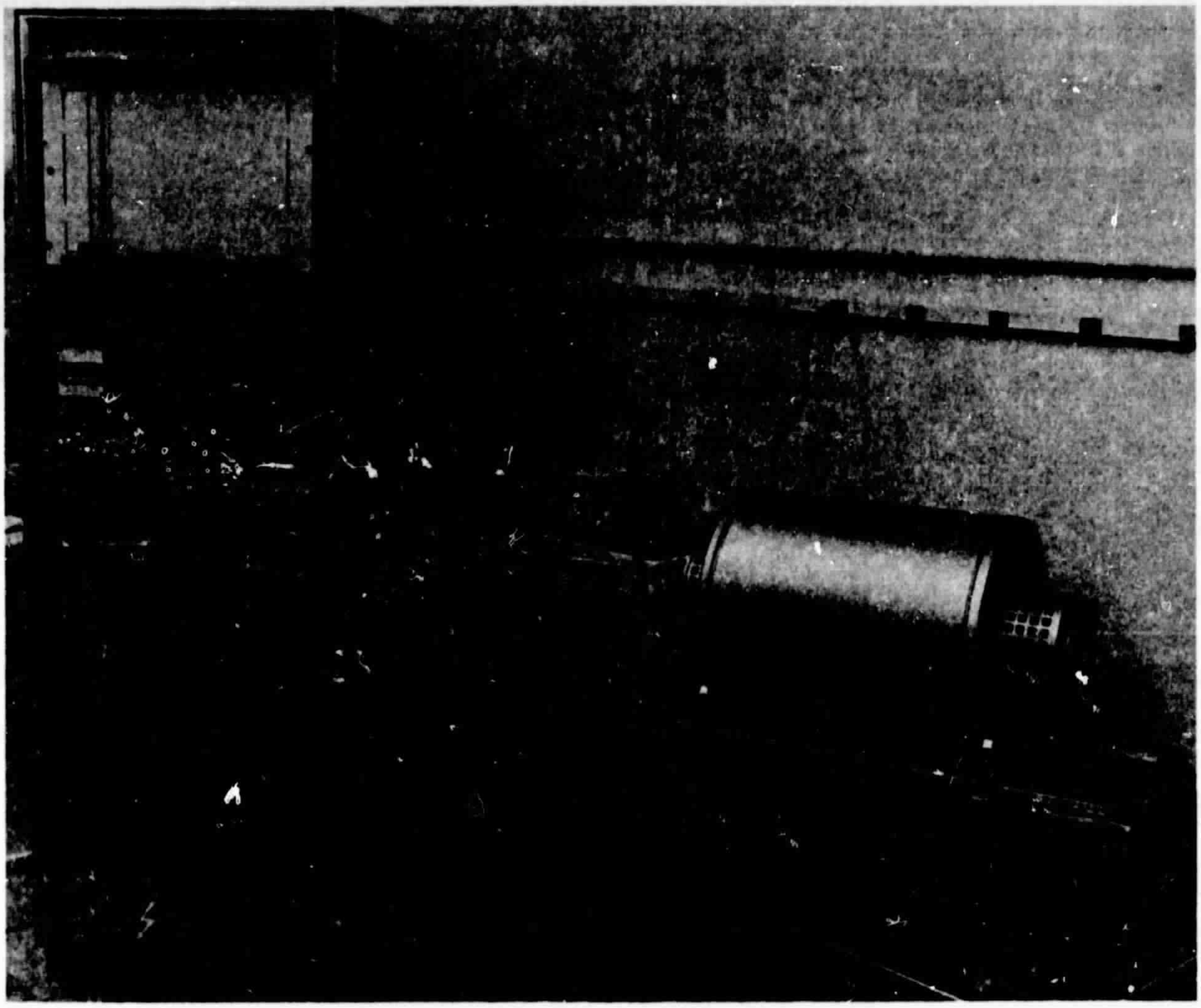


Figure 20 Dilatometer Test Apparatus at Ford

Modulus of rupture will be measured in 4-point bending on either of two Instron Universal Testing machines, a model 1125 (Figure 21) and a model 1122. The only significant difference between the machines is the load range, the model 1125 having a capacity of 100 KN (20,000 lb.) while the 1122 can go only to 5 KN (1,000 lb.). Instrons will be fitted with model 1700 MLC Rapid-Temp. furnaces made by the CM Corporation. These furnaces use molybdenum disilicide heating elements and have a temperature range to 1600°C (2910°F). Loading of the test fixtures in the furnace is accomplished through 25.4mm (1.0 inch) diameter recrystallized silicon carbide rods (Norton "Crystar") which extend out of the furnace to water-cooled fixtures which protect the load cell and loading frame from excessive temperature. The 4-point testing fixture itself is machined from hot pressed silicon carbide (Norton NC-203) (Figure 22). The fixture is self-aligning, simple and durable.

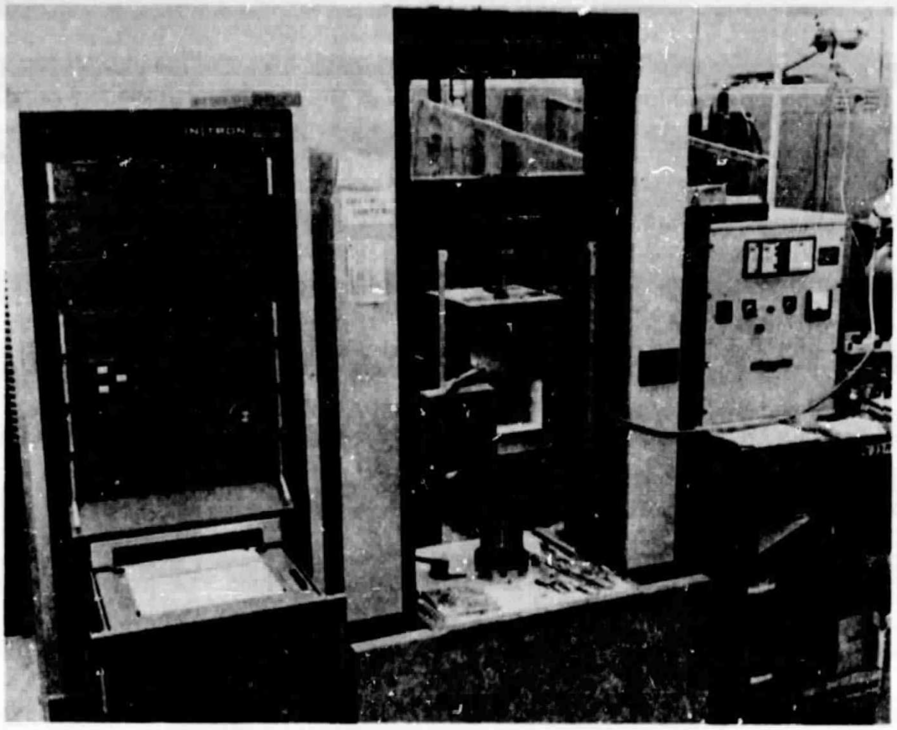


Figure 21 Room Temperature and Hot MOR Test Apparatus at Ford

Figure 22 Four-Point MOR Bend Test Fixture with Test Sample Installed

Samples will be tested at four temperatures and three different rates (if necessary). From the fracture load, the modulus of rupture can be calculated using elastic beam theory. The resulting data sets are then further reduced to statistical distribution parameters using the most-likelihood estimator (MLE) fit to the Weibull model. The resulting distribution is described by two terms, the characteristic value θ, defined as that strength by which 63.2% of the specimens would fail, and the Weibull modulus m, which is an indication of the scatter of the data. In order to obtain an acceptable degree of confidence, a minimum of 30 samples for each data set will be tested. Data will be acquired at four temperature levels: ambient, 1000, 1100 and 1204°C (1830, 2010 and 2200°F).

III. C. Status

A subcontract purchase order has been placed with IITRI for their part of the physical property characterization. Ford will be supplying finish machined test samples as soon as they are made available.

A purchase order has also been placed with Bomas for test specimen machining. The billets which Ford and Carborundum will be fabricating will be finish machined into the individual test specimens required for the material characterization effort.

Conversion of a dilatometer was completed at Ford to increase the maximum operating limit from 1000°C (1830°F) to in excess of 1200°C (2200°F) to meet the needs of this program.

Redesign of the rigid four-point, hot MOR fixture was completed (Figure 23). Special diamond coated, contoured grinding wheels for machining the load contact surfaces were designed and procured. Three complete sets of fixture pieces are being fabricated from Norton hot pressed NC-203 SiC material. A hardened steel duplicate of the SiC fixtures has also been fabricated.

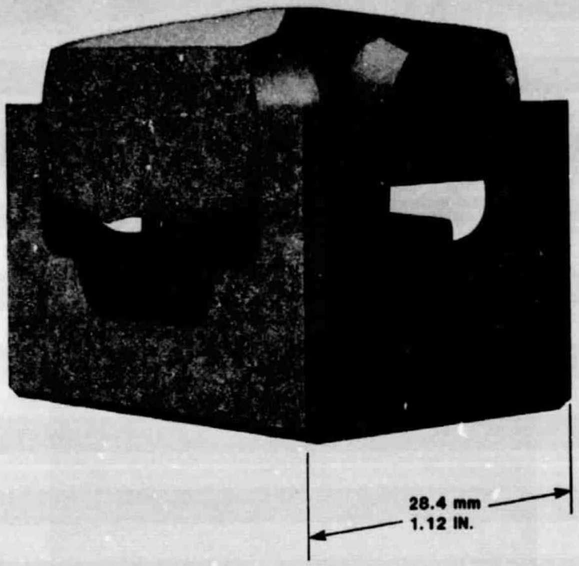


Figure 23 Redesigned Four-point Hot MOR Test Fixture

Discussions with the Task II sub-contractors raised some question regarding the MOR bar flatness requirements versus the as-cast or as-molded processing capabilities. These questions have precipitated an investigation of the non-flatness effect on test results from the rigid 4-point bend fixture.

A quantity of available, Ford fabricated, slip cast Si_3N_4 MOR bars were inspected as part of the non-flatness study. Surface flatness measurements were obtained and the bars categorized in an attempt to predict those likely to have significant stresses above the pure bending produced with the fixture. Four-point fracture load results showed no correlation with non-flatness, suggesting that the four-point bend strength was predominately flaw controlled.

A flexible seven-pin four-point MOR bar test fixture designed by Battelle has been rescaled for the same 9.5 x 19.0mm (.375 x .75 inch) span of the rigid fixtures on order. One fixture is being fabricated for use in room temperature correlation studies of MOR results obtained on un-machined test bars evaluated in the two types of fixtures.

III. D. Problem Areas

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No problem areas at this point in the program.

III. E. Work Planned

Test fixture fabrication for the MOR characterization will be completed.

Physical property specimens will be finish machined where necessary and delivered to IITRI on an as-available basis. Present projections should allow for completion of physical data on the Ford Si_3N_4 material and Norton SiC material during the next six months. MOR strength characterization at Ford will be completed as samples are submitted. Present projections should allow for complete characterization of the Ford Si_3N_4 material and partial evaluation of the AiResearch and Norton materials.

TASK IV — CERAMIC STATOR EVALUATION

IV. A. Scope of Work

All stators fabricated in Task II shall be subjected to preliminary tests before qualifying for simulated engine testing in the current Ford Engine Simulator Rig and Hot Flowpath Qualification rig. The preliminary tests shall include NDE, stator vane bend test, stator outer shroud pressure test, and a light-off qualification test. NDE tests shall include visual, dimensional, and radiographic inspections. The stator vane bend test, stator outer shroud pressure test, and light-off qualification test shall be conducted in accordance with the procedures outlined in Interim Report No. 11: Brittle Materials Design, High Temperature Gas Turbine Program[10].

The simulated engine testing, conducted in the Hot Flowpath Qualification Rig and the Engine Simulator Rig, must subject the stators to air flows and temperatures associated with a gas turbine powered vehicle operated over the EPA Composite Driving Cycle. The Stators must be tested in pairs, in line, simulating a two stage, axial turbine. Unleaded gasoline fuel should be used in the test rigs.

Periodic inspections of the stators shall be made during the simulated engine tests to monitor component performance. As a minimum, complete inspections shall be made after the light-off tests, after the initial 5 hours of durability testing and at 50 hour intervals thereafter. Complete inspections shall include removing the stators from the rig to check for component changes in weight, dimensions, and structural integrity. At least 1000 hours of simulated engine testing must be provided in the program.

Reliability prediction estimates must be prepared and compared to actual performance for each ceramic material to be subjected to simulated engine testing.

For stators that fail during testing, a post test analysis must be conducted to define the most likely cause of failure.

IV. B. Technical Approach

All the Task II stators received for evaluation will be subject to "as received" NDE testing. These tests include 30X visual inspection of the stator for surface imperfections, radiographic inspection to detect internal flaws and dimensional inspection. Documentation of these inspection results will be maintained for use in correlation with test results.

Preliminary screening tests, which will be used to qualify stators for duty cycle durability evaluation, consist of the stator vane bend test, the outer shroud pressure test and the 10 light test.

The stator vane bend test is intended to eliminate poor quality parts and permit rapid correlation between visual inspection data and the mechanical integrity of the stator vane. The test fixture, shown in Figure 24, consists of a series of twenty-five 6.35mm (0.250 inch) diameter pins which load the vanes at the inner shroud of each vane. The inner shroud is separated from its neighbor by a thin slot, thus each vane is loaded independently. The part is secured in the fixture by means of six clamps around the outer shroud. A variable load is applied via a hydraulic system to the inner shroud by the pins. The stator can be tested by placing the leading and trailing edges of the vanes in tension or inverting the stator and applying tension to the vane suction surface. A load of 84.5N (19 pounds) on each vane has been successful in qualifying Ford Si_3N_4 stators.

Figure 24 Stator Vane Mechanical Test Fixture

In the outer shroud pressure test, stators having defects in the outer shroud, which are likely to cause failure in durability testing, can be eliminated. In this test the stator is supported between two flat steel plates and a pressure is applied to the inner diameter of the outer shroud, putting the shroud in tension (Figure 25). A pressure load which produces 41.4MPa (6000 psi) tensile stress in the shroud has been successfully used with the Ford Si_3N_4 stators to provide reasonable assurance for light-off qualification survival.

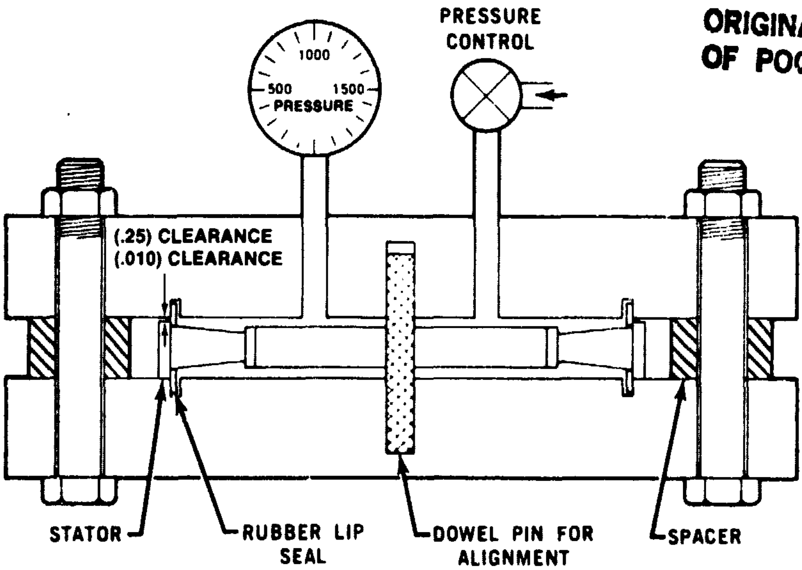

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Figure 25 Stator Outer Shroud Pressure Test Fixture

Light-off and shutdown transient testing will be conducted in the Engine Simulator Rig which is essentially a Ford Model 820 engine with the rotors removed. Figure 26 shows a photograph of this rig with a ceramic stator being installed. Test stators are installed in their normal position and engine light-off speed is established. When light-off is achieved the speed is ramped to 55% while the temperature is maintained at 1054°C (1930°F). Initially a series of 10 lights are made as outlined in Table 4. Typical light-off and shutdown thermal transients are shown in Figures 27 & 28.

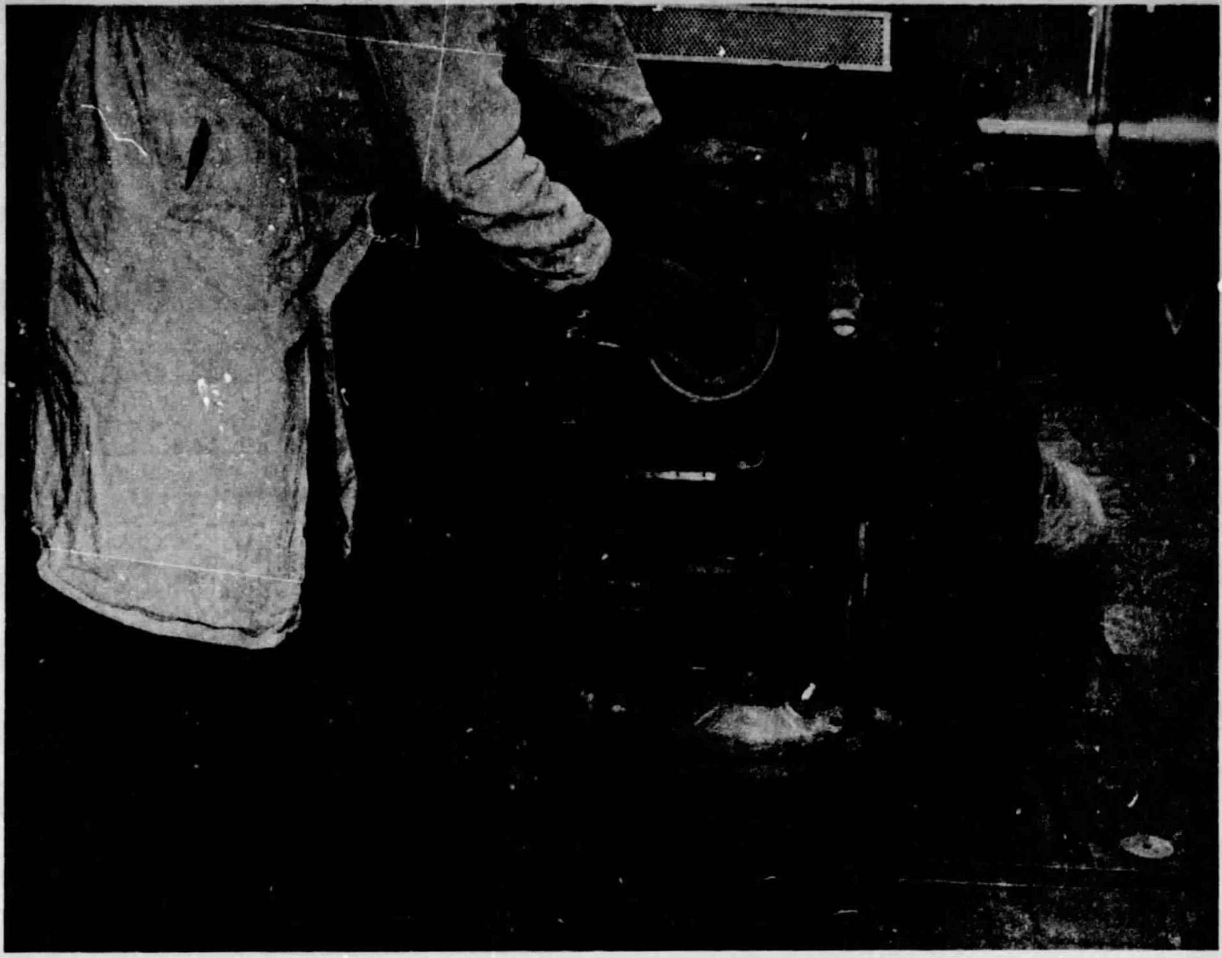

Figure 26 Engine Simulator Rig Showing Ceramic Stator Being Installed

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Number of Light	Light-Off Temperatures*, °C (°F)	Hold Time at 1054°C (1930°F) (Seconds)
1	21 (70)	30
2-5	66 (150)	30
6-9	66 (150)	60
10	66 (150)	300

Total Number of Light-Offs — 10
Total Time at temperature — 420 seconds.
* Forced cooling used between lights to achieve these temperatures.

Table 4. Light-Off Qualification Test Schedule — 10 Light Test

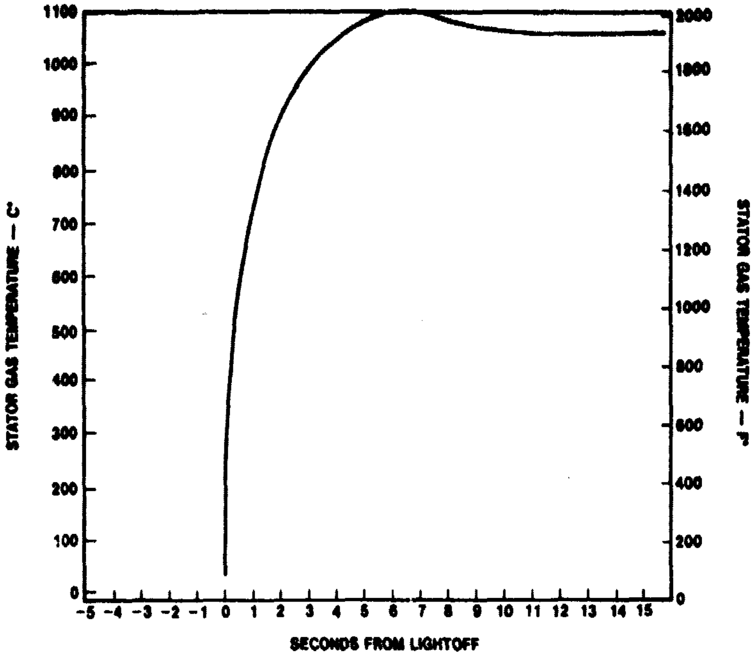

Figure 27 Typical Light Off Transient — Light Off Qualification Test

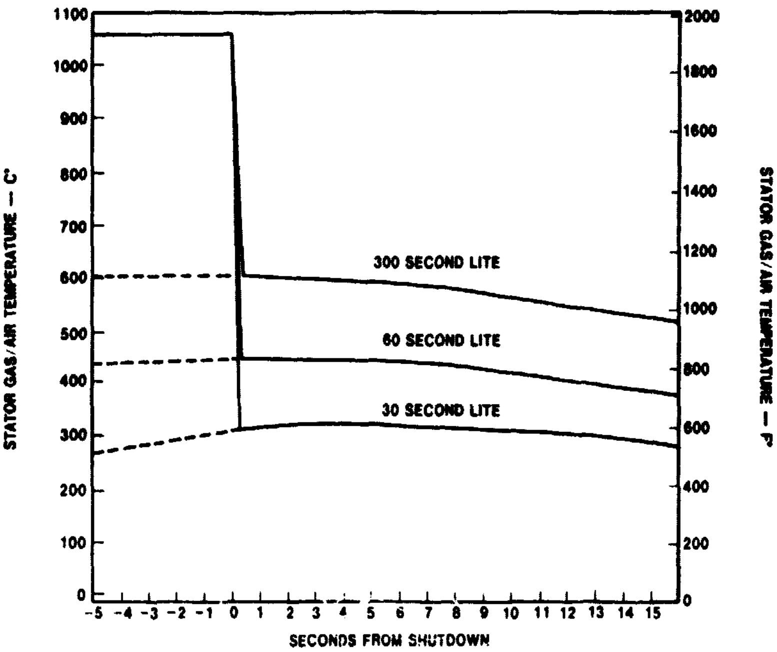

Figure 28 Typical Cool Down Transients — Light Off Qualification Test

Since the vane bend test and shroud pressure tests were developed specifically for the Ford Si_3N_4 stators, only Ford stators will be automatically subjected to those tests. In the case of the outside ceramic suppliers' stators, a fraction (about 1/4) of those submitted will be initially checked. The balance will be held in reserve until some results have been obtained from the light-off qualification test and initial durability evaluation.

The durability test will evaluate stator life under simulated engine duty cycle conditions. The specific durability cycle developed for this program is shown in Figure 29. It combines an accumulation of time at various airflow rates of 0.32, 0.41 and 0.64 kg/sec (0.7, 0.93 & 1.40 #/sec) with typical thermal transients for an automotive gas turbine. A basic four hour cycle will be run with varying airflow rates. Superimposed on the airflow variations are one-minute temperature cycles. The temperature starts from 704°C (1300°F), rises rapidly to and holds at 1121, 1177 or 1204°C (2050, 2150 and 2200°F), depending on the airflow level, then drops sharply to 927°C (1700°F) followed by a slow decay to the 704°C (1300°F) starting level.

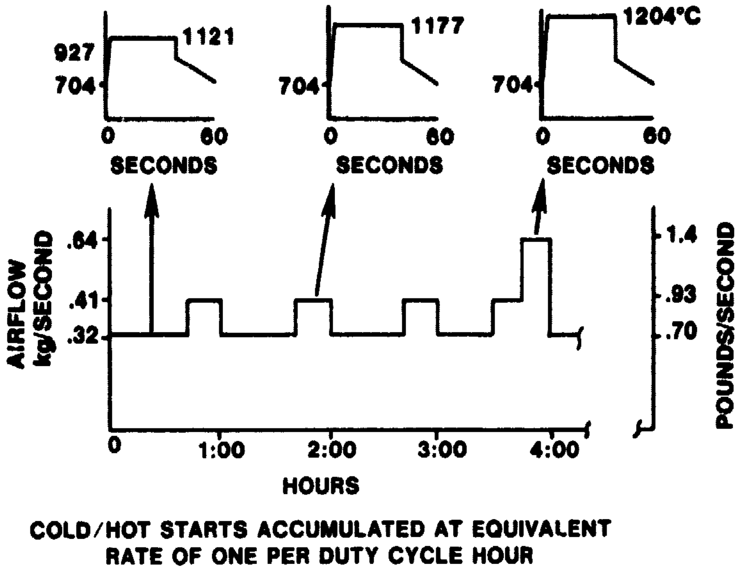

Figure 29 Durability Duty Cycle, Airflow and Temperature Schedules

Duty cycle durability testing will be performed in the Ford Hot Flowpath Qualification Rig (FPQR). A rig crossection is shown in Figure 30. This rig and its associated controls were originally designed for steady state operation. In order to insure duty cycle repeatability, an automatic control system will be designed and installed.

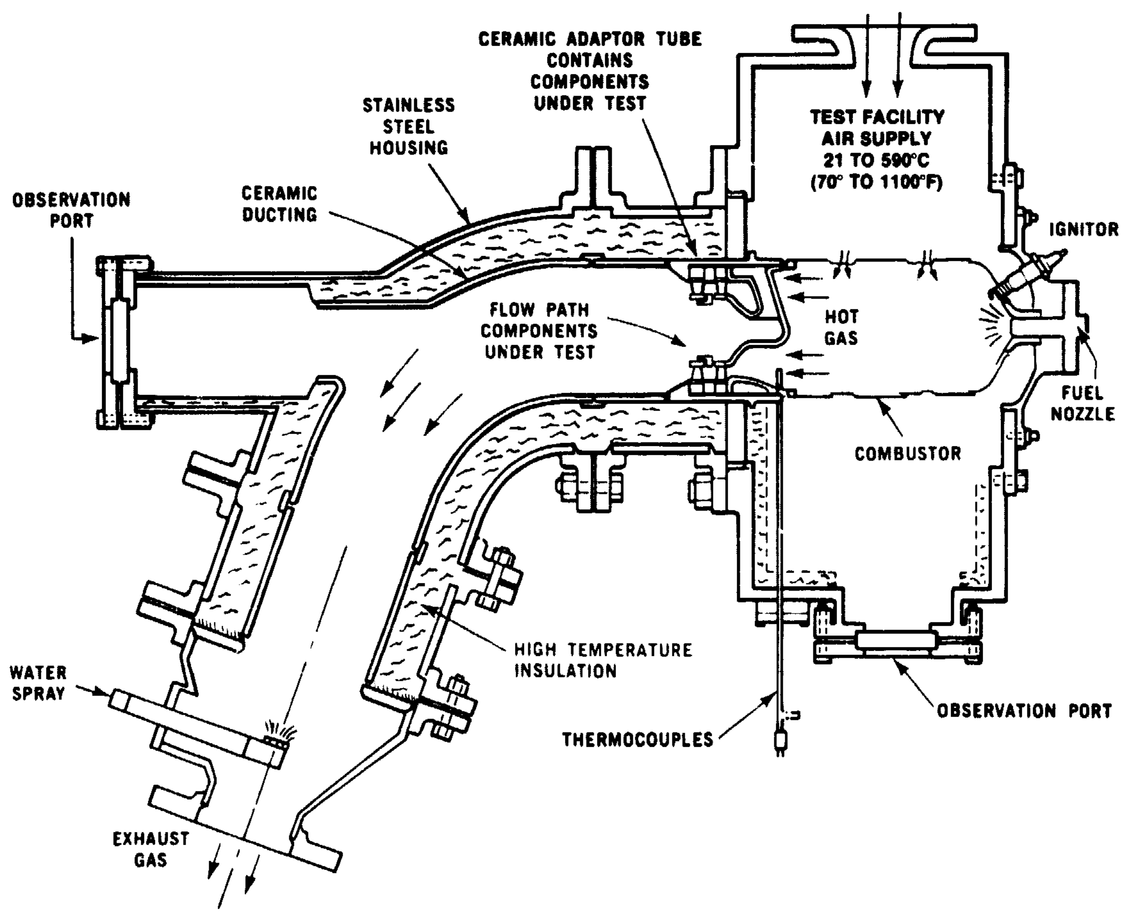

Figure 30 Duty Cycle Durability Test Rig

Durability testing will commence as soon as rig preparation is completed and stators are available. Qualified parts will be tested in pairs for an initial one cycle (4 hours) and then NDE inspected for weight gain, visual integrity and dimensional changes. Selected stators will then continue on duty cycle testing and will be removed for periodic NDE inspection and accumulation of simulated light-offs at approximately 50 hour intervals.

Duty cycle light-off testing will be performed in the Engine Simulator Rig on an equivalent one light-off per accumulated hour of duty cycle durability.

IV. C. Status

The main activity on the Task IV effort has been concerned with the preparation and automation of the FPQR. Automatic control of the test rig will be accomplished using a programmable analog control system.

A control specification has been completed describing the functional and sequencing requirements for the proposed duty cycle. The specification has been transmitted to the prospective vendor and reviewed to identify specific design data needed and transducer requirements. A purchase order has been placed with Ultra Electronics Incorporated for the control system and necessary transducers.

Sixty-nine hours of rig hot running time have been accumulated at discrete points of the proposed duty cycle during the report period. Testing has been conducted to check out a new design high temperature thermocouple, determine time constant data for thermocouples to be used in the automated system, generate design data for automating the rig cooling water system and measuring the radial temperature gradient at the test section immediately ahead of the test stator.

The typical radial gradients for the original design FPQR combustor are shown in Figure 31 for an inlet temperature of 566°C (1050°F). Gradients at the minimum cycle temperature of 704°C (1300°F) could not be obtained because the lean blow-out limit of this combustor was approximately 816°C (1500°F). Several available alternate combustor configurations have been evaluated for improvement in the lean blow-out characteristics. A combustor assembly with a ceramic flame tube and special metal dome was included in the evaluation and resulted in a decrease in the lean blow-out limit by more than 93°C (200°F). Similar dilution hole geometry pattern was produced in a modified metal combustor and produced similar lean blow-out characteristics. This combustor is being further evaluated for radial temperature gradients and carbon free operation over the complete range of the duty cycle.

IV. D. Problem Areas

Satisfactory combustor operation over the complete range of duty cycle conditions has yet to be achieved. A wide range of fuel/air ratios is demanded by the duty cycle necessitating a combustor design which avoids flame out at the lean end of the range while preventing excessively rich conditions, conducive to carbon formation, at the other end.

IV. E. Work Planned

During the next six month period additional combustor development will be conducted to insure full range, trouble free operation. Cell preparation, installation and check out of the automatic duty cycle control system will be completed. NDE and qualification testing of Task II stators will be performed on available components. Duty cycle durability evaluation will begin.

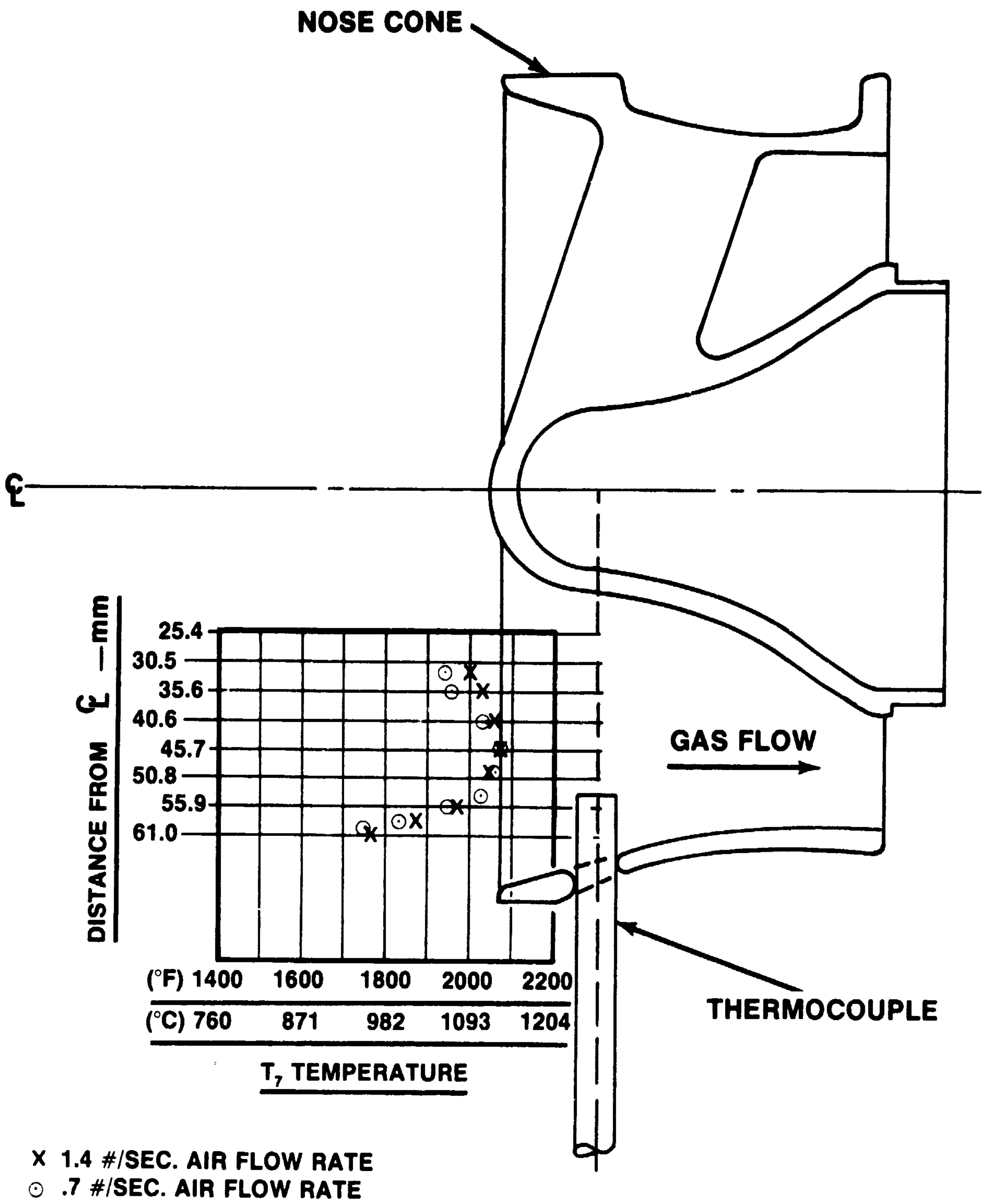

Figure 31 Combustor Exit Temperature Radial Gradient, Duty Cycle Durability Test Rig, Original Design Combustor

REFERENCES

1. McNally, W. D., "Fortran Program for Calculating Compressible Laminar and Turbulent Boundary Layers in Arbitrary Pressure Gradients", NASA TND-5681, Lewis Research Center, Cleveland, Ohio, May, 1970.

2. Katsanis, T., "Fortran Program for Calculating Transonic Velocities on a Blade-to Blade Turbomachine Stream Surface", NASA TND-5427, Lewis Research Center, Cleveland, Ohio, September, 1969.

3. Zysina-Molozhen, L. M. and Uskov, I. B., "Experimental Investigation of the Heat Transfer on the End Wall of a Blade Channel (in turbines)", Translated from Russian for NASA by the Israel Program for Scientific Translations.

4. Hui, H. and Peterson, F., "Three-Dimensional Transient Heat Transfer Analysis Using a Finite Element Procedure", Engineering/Analysis Corporation, Redondo Beach, California, August, 1971.

5. McNally, W. D., "Fortran Program for Calculating Aerodynamic Forces from Pressure or Velocity Distributions on Blade Section", NASA TMX-2123, Lewis Research Center, Cleveland, Ohio 44135, November, 1970.

6. Wilson, E. L., "Finite Element Analysis of Mine Structures", Dept. of Structural Engineering, University of California, Final Report (PB-220 141) to Denver Mining Research Center, U.S. Department of Interior, September, 1972.

7. Evans, A. G., and Weiderhorn, S. M., "Crack Propagation and Failure Prediction in Silicon Nitride at Elevated Temperature", *Journal of Materials Science*, Vol. 9, 1974, pp. 270-278.

8. Norris, D. M. and Grantham, P. V., "Thermal Stress Analysis of a Ceramic Gas Turbine Stator Blade", Lawrence Livermore Laboratory, Report UCRL-51923, October 3, 1975.

9. McLean, A. F., Fisher, E. A., Bratton, R. J., Miller, D G., "Brittle Materials Design, High Temperature Gas Turbine", AMMRC-CTR-75-8, Interim Report, April, 1975.

10. McLean, A. F., Fisher, E. A., "Brittle Materials Design, High Temperature Gas Turbine", AMMRC-CTR-77-20, Interim Report, August, 1977.